The Estimation of Radiation Exposure for Arcsecond Pico Star Tracker (APST) in Low Earth Orbit

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In general COTS components have radiation tolerance of 1-10 Krad/year and untested components which are made up of silicon is estimated to have radiation tolerance up to 5 Krad. The primary idea of this paper is to estimate the Total Ionizing Dose (TID) of silicon and Single Event Upset (SEU) rates of the COTS components in LEO, using Space Environment Information System (SPENVIS) software. This analysis are performed for the orbital altitude of 400 to 600 km, inclination of 90° for one year. The result estimates that the target material silicon, without shielding acquired TID of 3.04 Mrad. The Aluminum shieling of 2mm and 3mm thickness reduces the TID to 3.04 Krad and 1.39 Krad respectively. The shielding of 2mm is optimum for COTS in LEO. At orbital inclination of 0°, 28° with a shielding of 2mm, the TID is 0.014Krad and 0.56 Krad respectively, but at 60° to 90° the TID increased to 3 Krad. The SEU rate varies for each device based on design, manufacturing technology, LET threshold, and maximum sensitive surface of the component. The results implies in worst case, bipolar, MOS, RAM device have error rate of 4.92 errors/bit-day, 10^{-1} errors/bit-day, 10^{-3} errors/bit-day respectively. The radiation testing procedures for TID are detailed.

Key Words: Space radiation, radiation effects, COTS, SPENVIS, TID, SEU, radiation shielding, radiation testing

1. Introduction

The artificial satellites around the earth are always vulnerable to the charged particles from radiative sources. This affects the reliability and endurance of the electronics in the satellite. The energy, flux and fluency of these charged particles varies according to the altitude and inclination of the orbit. The radiation effects from these particles not only cause degradation but can also cause failure of electronics and electrical system of satellite. It can be overcome either by using radiation hardened devices or qualifying commercial devices by radiation testing. The radiation hardened devices are reliable for space application. The problem is hardened devices are expensive, less available and fabricated using non state of art technologies. The COTS (Commercially off-the- shelf) components are affordable and accessible by private space organizations. But the COTS components are not designed for space application. It is vulnerable to radiation effects. The commercial components can be qualified by radiation ground testing to determine if the component will survive in the radiation environment of the target orbit.

This paper deals with theoretical study about the radiation sources and radiation effects. The orbital experience about radiation exposure from various space missions are detailed. Estimation of the TID acquired by silicon in orbit using SPENVIS radiation model, required shielding for the component in the orbit, in addition SEU rates for various electronic device is estimated. This analysis is performed to estimate the radiation exposure for APST (Arcsecond Pico Star Tracker) in Low Earth Orbit. The TID radiation testing procedure for COTS, test-setup and test plan to qualify the COTS components for orbital operation are detailed.

2. Radiation Sources

The charged particles in space are broadly classified into trapped and transient particles. The trapped particles are known as Van Allen belt which are present within the magnetosphere of the earth. The transient particles are classified into solar particles and GCR (Galactic Cosmic Rays). In general these transient particles are trapped in the earth's magnetosphere. The Figure 1 shows the source of radiation in space.

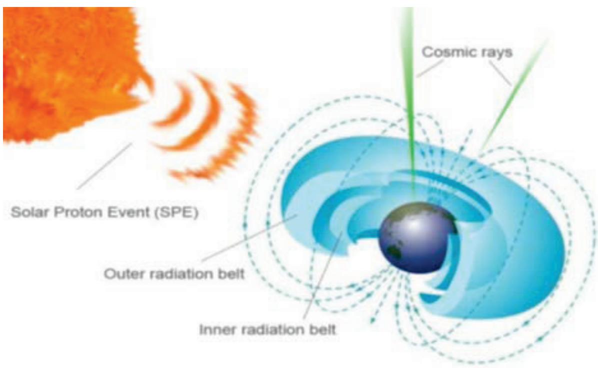

Fig.1. Radiation sources in space [1]

2.1. Trapped particles in Van Allen belt

The radiation belt mainly consists of electron, proton and heavy ion. The radiation belt is divided into two zones, inner belt and outer belt. The inner belt starts between 300 to 1000 km and lasts until 10,000 km. The outer belt starts at 10,000 km and spreads beyond 36,000 km. The trapped proton and electron population varies according to the altitude. The

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proton above 10 MeV lies in the altitude below 2,000 km. In the low altitudes at south Atlantic the energy of protons is higher than 30 MeV. The lower energy proton less than 1.0 MeV spreads over wide region until geosynchronous altitude. The typical satellite shielding can protect it from the protons with energy below 10 MeV. The trapped electron with maximum energy of 7 MeV lies in the outer belt. The inner belt electrons contain maximum energy of 5 MeV. [2) - 5)]

2.2. Solar Particle Events

The solar flares and coronal mass ejection events occur in the sun. It ejects electron, proton, heavy ions and alpha particles. In solar flares (90-95%) the emitted particles are protons. Heavy ions constitute only small percent of the emitted particles. The electrons from solar eruption have low energy. The protons from solar flares sustain for few hours to few days and it has energy till 100 MeV. Contribution of heavy ions are less when compared to heavy ions form the cosmic radiation. The solar events are patterned base on the eleven year solar cycle. The high fluence of proton event occurs most in solar maximum. [2) - 5)]

2.3. Galactic Cosmic Radiation

The GCR originates from outside the solar system. During solar minimum the exposure of GCR is more. The Galactic cosmic radiation contains about 85% protons and 14% alpha particles and 1% heavier nuclei. Comparing the solar eruption and radiation belt protons, the effect of GCR is less in equator and more in poles due to less geomagnetic shielding. It has low flux but high energy. The GCR mainly considered for SEE (Single Event Effects) in electronics. The main source for the radiation effects in electronics in orbit is due to proton and electron in Van Allen belt. The second cause is due to solar protons and third source is GCR heavy ions. [3) - 5)]

2.4. Solar Cycle

The flux of those sources is affected by the activity of the solar cycle. The solar cycle contain two phases, the solar minimum and solar maximum. The duration of the solar cycle is eleven year, four years of solar minimum and seven years of solar maximum. The fluence, flux and energy of the particle vary based on the altitude and inclination of the orbit. The Table 1 shows flux of the sources during solar cycle.

Table 1.Flux of the charged particle during solar cycle. [4)]

Particle type	Solar cycle & variation in flux	Types of orbit affected
Trapped – Protons	Solar Min - Higher Solar Max – Lower	LEO, HEO, Transfer orbits
Trapped – Electrons	Solar Min – Lower Solar Max – Higher	LEO, GEO, HEO, Transfer orbits
Transient GCR ions	Solar Min – Higher Solar Max – Lower	LEO, GEO, HEO
Transient Solar protons	During Solar Max only	LEO (I>45º), GEO, HEO
Transient Heavy ions	During Solar Max only	LEO, GEO, HEO, Interplanetary

3. Radiation Effects

The radiation effects on electronics in orbit are broadly classified into two types, cumulative effects and Single Event Effects (SEEs). The cumulative effects are minor defects which cause measurable effects and even failure over a period of time.

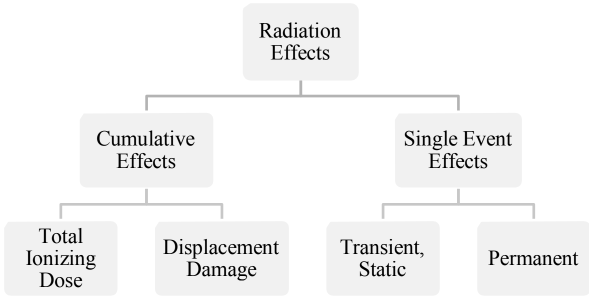

Fig.2. Classification of radiation effects. [6)]

3.1 Total Ionizing Dose (TID)

The electron, proton and heavy ions from the radiation sources cause ionization, when they incident on the matter (semi-conductor). The ionizing particles loss their energy when they travel through the matter and that energy is deposited in the matter. Energy loss of the particle is classified into two types; they are electronic energy loss and nuclear energy loss. The interaction with electron of the atom deals with electronic energy loss and interaction with nucleus of the atom deals with nuclear energy loss. The TID causes only electronic energy losses. The measure of total energy deposited per unit mass of the material through ionization is defined as Total Ionizing Dose (TID). TID is measured over period of time, the effect of ionization increases gradually over the mission duration. The TID is measured in Gray (GY) in SI system, but traditionally the total dose is measured in rads (1GY = 100 rad). In CMOS and CCD the effects would be increase in dark current and change in pixel amplifier gain. Change in power consumption and current leakage are the effects of TID. [4) 6) 7)]

3.2 Displacement Damage (DD)

The radiative particles traverse the crystalline material, displaces the atoms from the normal lattice sites and it deforms the material structure, it is known as displacement damage effect. This effect depends on incident particle type, incident particle energy, particle fluence (particle/cm^2) of the surrounding and the incident material. The displacement damage effect is estimated using NIEL (non-ionizing energy loss). In DD the material does not loose energy by ionization but by elastic/inelastic collision with nuclei in the material. This effect is more important for photo detector and electro-optic integrated circuit [4) – 6)]. The effects on CCD and CMOS image sensor are increase in dark current, reducing gain and Charge Transfer Efficiency (CTE), increases hot spots, and less responsivity.

3.3. Single Event Effect

The Single Event Effect is caused when a single charged particle pass through the device and losses their energy by ionizing the device. It deposits enough energy on the matter to cause a failure in a single strike. It might also cause nuclear interaction with the incident material. The SEE of the device is estimated by two parameters, Q_{crit} and LET (Linear Energy Transfer). The Q_{crit} is minimum amount of charge required to cause a soft error at any given node, it is measured in pico coulomb (pC). The silicon requires 22.5MeV of energy to generate 1 pC of charge (22.5 MeV is the stopping energy of silicon). When the deposited energy is higher than its stopping energy of the material, then it generates the charges at nodes. If the charge generated is higher than Q_{crit} then an SEE occurs in the device. When Q_{crit} for a device is increased then it's SEE rate is decreased.

The sensitivity of the device to SEE is characterized by LET versus cross section. The amount of energy transferred during ionization is given by LET function. It is measured in MeV.cm^2/g or KeV/μm. LET threshold is the minimum LET to cause an effect. The LET varies depending on incident particle mass, incident energy and angle of incidence. The number of upset or errors, divided by number of particle per cm^2 (fluence) is referred as cross section (σ). The saturation limit (σ_{lim}) is the cross section of the sensitive area. By the following four weibull parameters, LET threshold (LETth), saturation limit (σ_{lim}), width (W) and Power (S). SEU rates for a device can be generated by SPENVIS radiation model software. SEEs test can be performed in a particle accelerator. Mainly there are three types of SEEs, transient, static and permanent Single Event Effects. [4), 6) - 8)]

3.3.1 Permanent SEEs

These effects cause permanent damage or failure. Single Event Latchup (SEL), Single Event Burnout (SEB), Single Event Gate Rupture (SEGR) are categorized under permanent SEEs. SEL occurs in CMOS technologies. The sustained high-current state induced by a single-particle interaction is referred to as single-event latch-up (SEL). The latchup increase the current, if the power supply is maintained then the device is destroyed by thermal effect. By monitoring the current and power control circuit the damage can avoided. Single Event Burnout (SEB) occurs in power MOSFETs; the power devices are sensitive to SEB, when the device is in a biased off state. It's similar to SEL. The permanent damage of the device occur when short-circuit current induced across the high voltage junction. Single Event Gate Rupture (SEGR) also affects power MOSFET in the 'off' state. The incident particle forms a conduction path in a gate oxide, resulting in device damage.[4) 7)]

3.3.2 Static and Transient SEEs

This effects does not cause any permanent damage or failure, it cause errors (bits of information stored in logic circuit or in a storage device is changed) when the incident material is ionized. This effect is known as Single Event Upset (SEU). Static Random Access Memory (SRAM) and Dynamic Random Access Memory (DRAM) and other memory devices are affected by the SEU. By resetting, the device is operational. The Single Event Functional Interrupt (SEFI) is caused by ion strike; it leads to temporary non-functionality of the affected device. The transient SEEs cause variation in the amplitude of the signal. This effect is notable in most of the device. It mostly occurs in linear regulators and converters. The radiation effects due to different charged particles are summarized in Table 2. [8)]

Table 2. Radiation effects due to charged particles [8)]

Particle	Particle	Effects
Trapped	Protons	Total Dose, SEEs Displacement Damage Solar cell degradation
	Electrons	Total Dose Solar cell degradation
	Heavy Ions	SEEs, dose exposure for humans
Transient	Solar Protons	Total Dose , SEEs Displacement Damage Solar cell degradation
	Solar Heavy Ions	SEEs
	Galactic Cosmic Rays	SEEs, dose exposure for humans

4. Orbital Experience

The COTS components manufactured under various technologies like cmos, mos, rmos, fpga, bipolar, dram, sram, soi, sos, epi. Each of these technology reacts differently to the radiation and their effects differ. The radiation testing and parameter measurements should be designed based on the technology of the component. In general the COTS components have radiation tolerance of 1 – 10 Krad/year [9)] and untested COTS component (Si) has dose limit of 5 Krad [10)]. The Table 3 shows the required total dose for various orbits. The component is shielded by Aluminum with thickness of 100 mills (2.54 mm).

Table 3. Total dose requirements for various space missions [11)]

Description	Orbit	Operating time (years)	Total Dose (rad) (SiO_2)
Space station	500 km, 54°	10	5×10^3
High inclination earth orbiter	705 km, 98°	5	2×10^4
Geostationary	36,000 km	5	5×10^4
Mars surface exploration	NA	3	10^4
Mission near Jupiter	NA	9	1.5×10^5 - 2×10^6

The orbit of our mission is assumed to be LEO (400 to 600 km) polar orbit. According to the high inclination earth orbit in Table 3 with shielding of 100 mills (2.54 mm), the total dose of (SiO_2) for one year is 4 Krad. The 4 Krad is within our specified limit of dose of (1-10 Krad). The altitude of ISS is apogee-437 km and perigee-361 km and the inclination of the orbit is 51.59°. At ISS orbit the total dose acquired for one year is 0.5 Krad for a shielding of 2.54mm thickness.

5. Arcsecond Pico Star Tracker (APST)

The SNUSAT-2 is a technology demonstration mission in nanosatellite platform. One of the technical objectives of this mission is to develop Pico Star Tracker which can estimate the pointing knowledge of the satellite in arcsecond accuracy. The star trackers in commercial market are heavy, larger in size, power consuming, and costly for nanosatellites. Hence optimized Arcsecond Pico Star Tracker (APST) for SNUSAT-2 is under development in Seoul National University. The APST is designed based on the mission requirement and limitations of nanosatellite. The main components of APST are image sensor, imaging lens, and processor, DRAM and Flash which are selected from COTS (Commercially off-the-shelf). The baffle for the star tracker is designed and will be fabricated in-house. The Figure 3 below shows the design of APST. It contain three main section, baffle, Optics, and processing which are labeled as A, B, and C respectively in Figure 3. The processing section include two PCB which contain MT9P031 (Active Pixel Sensor), STM ARM Cortex M-4 processor, SDRAM and Flash memory. The dimension of APST is 87 x 48 mm^2. The COTS components are not designed and manufactured to withstand the radiation. Hence the electronics and optics in APST have to undergo radiation testing to estimate the radiation tolerance of the components. Based on the radiation tolerance of the component, the required amount of shielding can be estimated. This paper estimates the radiation in LEO and effects due to TID, SEU, and required amount of shielding. Also the radiation testing procedure for TID are detailed. The TID radiation testing will conducted to validate the APST for space operations.

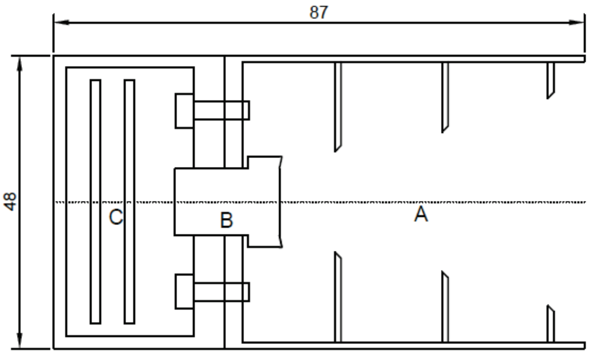

Fig.3 Design of Arcsecond Pico Star Tracker (APST)

6. SPENVIS radiation model

SPENVIS is used for estimating the Total Ionizing Dose (TID) for silicon (Si) and SEU rates. The first step is the input of spacecraft trajectories and mission duration. The altitude and inclination of the orbit is assumed to be perigee = 400 km, apogee = 600 km, inclination = 90º. Estimation are made for mission duration of 3, 6, and 12 months. The radiation sources are selected and their properties are defined. The defined radiation sources in SPENVIS are,

i. Trapped particles radiation model
ii. Long- term solar particles fluences
iii. Galactic cosmic ray fluxes

The trapped particle flux model have three different proton and electron modules. The AP-9 proton model and AE-9 electron model are selected because it covers the full spatial and spectral range of the radiation belts.

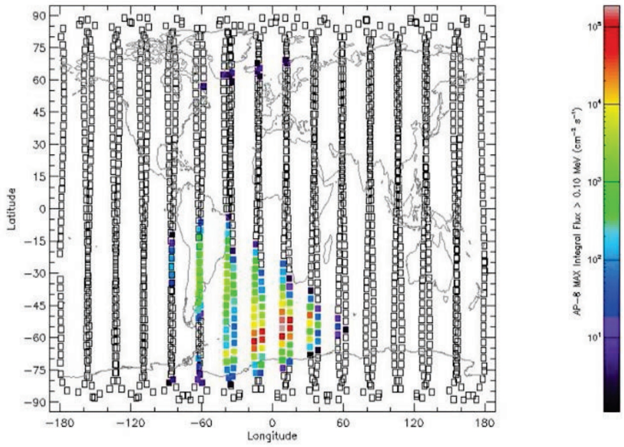

Fig.4. Trapped proton flux distribution over altitude 400- 600 km

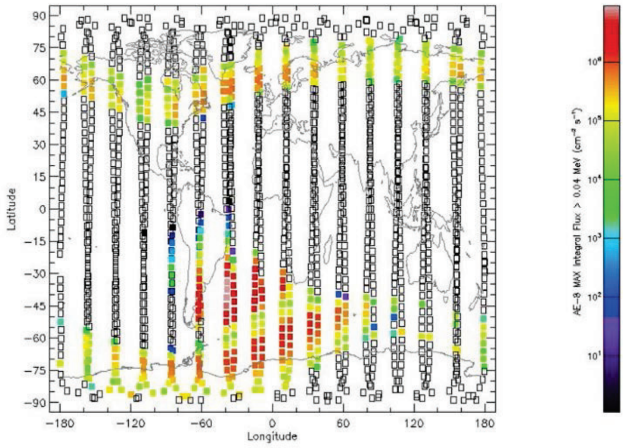

Fig.5. Trapped electron flux distribution over altitude 400- 600 km

The Figure 4 & 5 shows the distribution of proton and electron at an altitude of 400 to 600 km. The proton are distributed over particular region from -10º to -80º latitude and -60º to 60º longitude. The most of the protons are present over south Atlantic, it's known as the south Atlantic anomaly. The trapped electrons are more widely distributed over the earth than the protons. The electrons are densely populated in both northern and southern hemisphere. The satellite with higher inclination encounters more electron than proton. The electrons are located over 45º to 75º N and -15º to -90º S latitude. In the longitude it's spread over -180º to 180º.

The Long-term solar particles fluences model have the inputs from solar particles. The worst- case scenario module is selected for the solar particle fluence. The solar maximum is chosen. The Galactic Cosmic Ray flux model, have the inputs from cosmic particles. The ISO 15390 model and solar minimum is selected. GCR flux is more in solar minimum. The shielddose-2 model is used for shielding geometry. The shielding material is Aluminum. The shielding geometry is "center of Al sphere". The source of radiation is isotropic. The target material is analyzed with various shielding thickness of (Al) form 10^{-4}mm to 3mm to find out the corresponding total dose.

7. Radiation model results

7.1. Total Ionizing Dose

The Table 4 to table 6 contain the estimated TID for 1 year, 6 months, and 1 month respectively. Each table contains the Aluminum shielding of various thicknesses, TID in Krad, radiation dose due to trapped electron, Bremsstrahlung, trapped protons and solar protons. When electron is deflected by heavy particles then part of the energy (rad) is emitted, it is known as bremsstrahlung. The first row of the Table 4 contains the TID for a shielding of 10^{-4} mm. This is minimum possible shielding thickness available in SPENVIS for TID calculation. We consider this minimum thickness (10^{-4} mm), as a component without shielding. The component without shielding in the orbit over a period of one year acquires the TID of 3040 Krad. According to the first limitation, the COTS component should not exceed the Total dose of 1-10 Krad/year. The component would able to survive with 5.9 Krad of total dose for duration of one year with a shielding of 1.4 mm. The component with 2mm of shielding in orbit over one year absorb total dose of 3.04 Krad.

Using 2mm thickness of Aluminum, the trapped electron produce dose of 1.4 Krad radiation around in polar orbit, solar proton produce dose of 1.31 Krad, trapped protons dose of 0.3 Krad, bremsstrahlung produce dose of 0.015 Krad. The Total mission dose is 3.04 Krad. The value of 3.04 Krad is within the criteria of COTs component of 1- 10 Krad. The component without shielding should be irradiated in the radiation test facility up to the total dose of 5Krad. If the component would survive the irradiation without functional failure up to 4.56 Krad (which is 1.5×3.04 Krad, based on Radiation Design Margin) then the component would survive in the orbit with shielding of 2mm for one year. The duration of the mission in the orbit is classified into maximum of one year, minimum of 1 month and in average of 6 months. The total absorbed dose in 6 months with 2mm shielding is 1.52 Krad and for one month it is 0.28 Krad.

Table 4. One year -Total mission dose

Al thickness (mm)	TID (Krad)	Trapped Electrons (Krad)	Bremsst -rahlung (Krad)	Trapped Protons (Krad)	Solar Protons (Krad)
0.0001	3040	670	0.48	987	1390
1.4	5.9	3.5	0.024	0.42	1.95
2	3.04	1.4	0.015	0.3	1.31
3	1.39	0.35	0.0094	0.21	0.81

Table 5. Six months - Total mission dose

Al thickness (mm)	TID (Krad)	Trapped electrons (Krad)	Bremsst-rahlung (Krad)	Trapped Protons (Krad)	Solar Protons (Krad)
0.0001	1520	336	0.24	495	697
1	5.38	3.67	0.018	0.3	1.38
2	1.52	0.7	0.0076	0.15	0.65

Table 6. One month - Total mission dose

Al thickness (mm)	TID (Krad)	Trapped electrons (Krad)	Bremsst-rahlung (Krad)	Trapped Protons (Krad)	Solar Protons (Krad)
0.0001	261	58.3	0.042	85.1	181
1	1.03	0.74	0.0038	0.051	0.23
2	0.28	0.14	0.0015	0.026	0.11

The Figure 6 shows the dose absorbed by Silicon at the center of Al sphere, for various thicknesses for a duration of one year. The graph contains the doses due to electrons, bremsstrahlung, trapped protons, solar protons and total dose. The magnitude of radiation dose varies depend on the altitude and inclination of orbit. To know difference in radiation level and particle fluence, the radiation model in SPENVIS is simulated for orbital inclinations of 0°, 28°, 60°, 90°, and apogee is 600 km and perigee is 400 km with (Al) shielding of 2 mm thickness for period of one year.

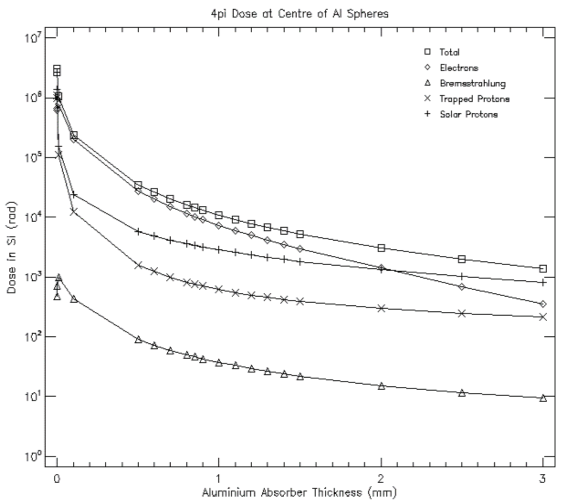

Fig.6 Radiation exposure various thickness of (Al) for one year.

The TID and particle fluence are estimated for different orbit inclinations, it is listed in the Table 7 & 8 respectively. Based on the results from simulation, TID absorbed by the silicon is higher in the poles and lower in the equator. As mentioned in theoretical section, the ionizing dose by electron is higher (0.37 Krad) near poles (60° to 89°) and lower in equator (0.014 Krad). The ionizing dose by trapped protons is higher in equator (0.015 Krad) and lower at poles (0.000002 rad). The ionizing doses by solar protons are zero in equator (0° to 30°) and higher in poles (1.32 Krad). The Total Ionizing Dose is lower (0.014 Krad) for orbital inclination of zero degree and higher (3.04 Krad) at 60° to 90°.

Table 7. TID variation for various orbital inclination at altitude 600-400 km

Orbit Inclination (deg)	TID (Krad)	Bremsst -rahlung (Krad)	Trapped Protons (Krad)	Trapped Electrons (Krad)	Solar Protons (Krad)
0°	0.014	0.00011	0.000002	0.014	0
28°	0.56	0.021	0.00034	0.54	0
60°	3.13	2.42	0.027	0.37	0.31
90°	3.04	1.4	0.015	0.3	1.32

The Table 8 Shows the particle fluence and GCR flux for different orbit inclinations. The numbers of electrons is higher at 60° to 90° (3.6×10^{13}) and less in equator (3.89×10^{9}). The number of trapped protons is more in equator and lower in poles when compared to electron fluence. The solar proton (transient) fluence is around equator (due to strong magnetosphere) and higher (3.15×10^{12}) in poles. GCR flux which is transient is higher in poles (6.78×10^{4}). The main reason for higher ionizing dose at pole is due to more transient particles at poles. The number of transient particles are higher in poles due to lack of magnetic flux.

Table 8. Particle fluence and GCR flux for various orbit inclination

Orbit Inclination (deg)	Electron Fluence (Particles /cm^2)	Proton fluence (Particles /cm^2)	Solar fluence (Particles /cm^2)	GCR Integr al flux
0°	3.89×10^{9}	2.89×10^{10}	0	4.79×10^{3}
28°	5×10^{11}	4.42×10^{11}	0	8.8×10^{3}
60°	3.6×10^{13}	7.66×10^{11}	7.39×10^{11}	4.6×10^{4}
90°	1.98×10^{13}	9.12×10^{11}	3.15×10^{12}	6.78×10^{4}

7.2. Single Event Upset rate (SEU)

The source of radiations is same as TID, and thickness of shielding is 1mm. The shape and volume of the device are considered as rectangular parallelepiped. There are two functions to measure the SEU rates, direction ionization upset rates and proton induce upset rates. But in this analysis only direct ionization uprate is considered. To determine the direct ionization upset rates, the four Weibull parameters are used. They are L_o, σ_{lim}, W and S, L_o is threshold of the LET value, saturation limit, W, S are width and power parameters respectively. All these parameters are detailed in previous section. By using these four parameters of COTS devices, the short term SEU rates of the device can be calculated using SPENVIS. The upset or error rate are represented in, per bit, bit per second, and bit per day. The Weibull parameters for 57 device are given by "E.L. Petersen" [12) 13)]. The first 45 device are COTS and it's not radiation tolerant and last 12 are radiation hardened. The device includes bipolar, mos, cmos, rmos, dram, sram. The SEU rate (bit per day) varies for each device based on design and manufacturing technology, LET threshold, maximum sensitive surface of the device.

The following are the upset or error rate of the COTS device (no radiation tolerant),

Bipolar = 1.91×10^{-2} to 4.92 error/bit-day
MOS, CMOS, RMOS = 4×10^{-5} to 9.45×10^{-1} error/bit-day
DRAM, SRAM = 1.88×10^{-4} to 4.92^{-3}

The upset or error rate for hardened device are mentioned in following,

DRAM (IBM 16M) = 8.51×10^{-7} error/bit-day
CMOS (R160-25) = 2.41×10^{-8} error/bit-day
EPI (6508RH) = 5.96×10^{-5} error/bit-day
SOS (TCS130) = 6.16×10^{-7} error/bit-day

8. Radiation testing procedure

This section displays general idea about radiation testing and procedures. To measure and confirm the quality of COTS, the Co_{60} (gamma rays) radiative source are used for measuring the Total Ionizing Dose effects in the device. The dose rate in space is not constant in the period of time. The mean dose rate in space is in the order of 0.0001 to 0.005 rad (Si)/s. During the time of solar flare the pulsed dose rate is in the order of 0.1 to 2 rad/s. But the mean dose rate very low to attain in the radiation test set up. It would take months to attain the TID if the mean dose rate is used for irradiation. The ESA/SCC 22900 has the standards for total dose steady-state irradiation test method. The dose rate classified into two levels, [14) - 16)]

Window 1 (Standard rate): 3.6 krad hr^{-1} to 36 krad hr^{-1}
Window 2 (Low rate): 36 rad hr^{-1} to 360 rad hr^{-1}

The standard rate is also known High dose rate; it is the most preferable one for COTS radiation test. High dose rate consumes less time and cost to attain the required TID. But the LDR almost creates the exact scenario in orbit and it's considered as the worst case scenario. The resistance of COTS components towards radiation differs highly with LDR and HDR. The components fail very earlier in Low dose rate when compared to High dose rate. According to the ESA/SCC, the total exposure time should be less than 96 hrs. The testing can be done for a single component or in system level. Testing each component separately is reliable; it helps in finding the exact radiation effects in the component. In the initial phase each COTS component can be tested separately, in the latter phase radiation testing can be done in system level. To test a component, minimum of five random samples is needed. In which four samples are irradiated in testing and the fifth one is a reference sample, which is not irradiated but the operation of the fifth sample is measured spontaneously. One of the four samples is in switch off state, to measure its radiation tolerance in switch off condition and remaining three is in on state. The DUT is mounted on the test circuit board. The distance between DUT and the radiation source is determined by the dose rate and homogeneity of the desired radiation. The distance shall be three times the value of semi-diagonal of the test board.

The radiation testing can be made in online or offline mode based on convenience. In online mode both irradiation of the device and the evaluation of the device are done in the same test setup and in offline mode irradiation and evaluation of the device are made in different places. In order to reduce the complexity of the shielding requirement of the measuring device the parameters measurement of the sensor are measured in offline mode. The measurement is made at intermediate dose levels and measurement should be made within maximum of 1hr [14)-16)]. The radiation testing consists of three phase, Pre-radiation testing, Radiation testing, Post radiation testing (annealing). Throughout the test the components can be biased based on requirement, ESA/SCC specifies that biasing the components would create the worst case scenario. The biasing has different affect for different technologies of the component. Care full biasing should be made based on the technology. But the components tested under both biased and un-biased condition able to analyze the tolerance of the component in detail.

The electronic devices which monitor the device should be checked. The pre-radiation testing is the electrical measurement made before the irradiation. The pre-radiation testing is done at room temperature. The second phase is the irradiation. The device is irradiated at the specified dose rate continuously until the component reach the specified total dose. The parameters of the components are monitored at intermediate dose level as explained before. The temperature during irradiation should be 20±10º C. The variation in temperature throughout the irradiation should not be more than 3º C. After the irradiation the third phase is the annealing. The annealing should begin within one hour of the completion of the irradiation and recommend annealing of 168 hrs at 25º C. Annealing is the important process in radiation testing. After the required irradiation, the components are affected. The percentage of damage varies for different components. The components overcome the damage and come to stable condition during the annealing time. The components are evaluated during annealing, if the component would overcome the damage and regain its performance gradually then it's validated for orbital operation. [14) - 16)]

9. Conclusion

The growth of pico and nanosatellite have led to high usage of COTS components for space operation. The author have worked in the development of pico and nanosatellite for past four years. The main reason for the failure of components in space is due to radiation exposure. In order to overcome this problems cubesats and nanosatellites are in need for estimating their radiation tolerance of the COTS components. But the methods to estimate the cause and effects are not detailed for cubesats and nanosats application in general. Hence the author prefer to shed the light on the radiation system for small scale commercial satellite. This paper displays the details the cause of space radiation and their effects on electronics in the satellite. Based on the information from previous space mission, the high inclination earth orbit with shielding of 2.54 mm, acquires the total dose of 4 Krad for one year.

The radiation exposure and required shielding in Low Earth Orbit for various orbital inclinations are estimated using SPENVIS. The inputs and method of analysis for SPENVIS is explained. In general the COTS components have radiation tolerance of 1 – 10 Krad/year and untested COTS component (Si) has dose limit of 5 Krad. Based on the SPENVIS results for the orbital altitude of 400 to 600 km and orbital inclination 90°, the radiation exposure can be reduced to 3.04 Krad using 2mm aluminum shielding for period of one year. If the component would survive the radiation testing for TID without functional failure up to 4.56 Krad (which is 1.5×3.04 Krad, based on Radiation Design Margin) then the component would survive in the orbit with shielding of 2mm for one year. One of the important factor is the Total Ionizing Dose is lower (0.014 Krad) for orbital inclination of zero degree and higher (3.04 Krad) at 60° to 90°. The SEU rates in worst case for bipolar, MOS, RAM based device has error rate of 4.92 errors/bit-day, 10^{-1} errors/bit-day, 10^{-3} errors/bit-day respectively. The radiation testing methods and procedure are detailed. Based on the above results, the TID radiation test will be performed to validate the Arcsecond Pico Star Tracker (APST).

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